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Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies

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ABSTRACT

In a world struggling for sustainable access to energy for all, renewable energy systems can be a solution to implement on isolated micro-communities. However, such an implementation is still a challenge.

This paper aims to review several types of projects developed in different micro-communities, namely small islands and remote villages, both in cases of real implementation and only evaluation studies. To do that, we analyzed documented projects in micro-communities with less than 100,000 people. We looked into different indicators related to island characterization, energy demand and proposed technical solution, in order to identify the determinant factors for the success of the implementation and how do they differ for islands and remote villages.

In islands, the main factors that influence the achievement of higher percentages of renewable source (RES) are the design of the existing energy system, the presence of a reliable energy storage system and the profile of the electricity demand, especially the occurrence of peak demand and seasonal oscillations. In general, the more popular configuration is a diesel/wind/photovoltaic.

In remote villages, higher percentages of RES are meet more easily in cases of very low demand, unstructured previous electric supply and the capability of using batteries as storage. The more popular configuration is the photovoltaic/diesel/batteries.

Having detailed demand information, estimates from the local renewable resources and the adequacy of the storage system are critical aspects for the system's design and its successful and reliable application.

This review also shows that the data reported in many different case studies is often incomplete, which makes it hard to benchmark and evaluate the different projects. Thus, this paper proposes a methodology to report the data regarding the design and implementation of hybrid renewable energy systems, to enable the comparison of future projects and contribute to the discovery of new insights about the implementability of these systems.

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1. Introduction

There are 1.2 billion people in the world (20% of world population) that still live without access to electricity [1]. The international community is concerned and seems committed to minimize this inequality of energy services between OECD and developing countries. Table 1 shows the universal modern energy access case for the 2010–2030 scenario [1], which suggests that 60% of the additional generation capacity and 63% of the total investment budget will be done on mini-grids and off-grid systems. This indicates that off-grid and mini-grid systems are emerging as the solution to improve welfare and socio-economic development of small isolated communities, as islands and remote villages.

Many of these communities spend over 20% of their income on energy [2], and due to the increasing costs of fuel generators (e.g. diesel) [3], the use of hybrid systems that incorporate renewable energy resources is a way to keep the systems more reliable and sustainable. These small communities are normally characterized by different types of constraints that span from small size, remoteness and vulnerability to external shocks (demand and supply side), narrow resource and exposure to global environmental challenges [4].

To help developing small and micro-communities, there are some interesting international cooperation programs running, with special focus on the development of renewable energy systems, such as: Small Island Developing States Network [5]; Energy Development in Island Nations [6]; ECOWAS for Renewable Energy and Energy Efficiency (ECREEE) [7]; European Island Network on Energy and Environment [8]; Green Islands Project [9]. We have also register an increase of forums [10] and joint initiatives [11], that aim to spread knowledge on renewable systems, case studies and sustainable energy policies.

This review intends to map the state of the art of Hybrid Renewable Energy Systems (HRES) in isolated micro-communities, especially in islands. This work aims to understand the system′s configuration, the main characteristics of the electricity demand and its dynamics, and the difficulties of implementation. Parsing the main limiting factors, we intend to pursue the development of a methodology to implement HRES with higher renewable penetration, allowing more autonomy, without forgetting reliability of supply and economic sustainability. We recognize that only an organized and standardized methodology of approach to HRES can bring clearance and success to the design of these systems. To achieve that, we have to take into account financial aspects, monitored and estimated demand, and an accurate forecasting of renewable potential.

This review also shows that the data reported in many different case studies is often incomplete or not so relevant, which makes it hard to benchmark and evaluate the different projects. Thus, this paper proposes a methodology to report the data regarding the design and implementation of micro-community hybrid renewable systems. This enables the comparison and benchmarking of future projects against the cases presented here and contribute to the discovery of new insights about the implementability of this type of system.

Table 1
Projections from the Universal Modern Energy Access Case Scenario for 2010–2030 [1].

	Isolated off-grid (%)	Mini-grid (%)	Grid connections (%)
Distribution of the additional generation of 952 TWh	18	42	40
Distribution of the additional investment of 700 billion $	20	43	37

2. Review approach

We listed various projects on micro-communities (islands and remote villages) with less than 100,000 people or equivalent in households, aiming to focus on smaller and isolated communities, with less than 10,000 people.

Later, we looked at the energy demand in these small communities and found that, albeit tourism is a relevant activity in most of the cases above 2000 inhabitants, there is few representativeness of other energy intensive sectors, such as industry or services. Thus, electricity demand in residential sector represents the largest share of total energy demand, which explains why this study focuses only on electricity demand.

Through the analysis of multiple case studies, we defined a list of indicators (Table 2) that we consider necessary to understand the energy system structure. These indicators take into account the community characterization and some technical data of the hybrid system that have been studied and/or implemented. With these indicators, we tried to analyze the implementation and success of these HRES, also taking into account the optimization methodologies′ used to maximize renewable penetration if used in the system design.

As each case study has its own specific goal (economic analysis, energy reliability, validation of a certain methodology, etc.) we encountered some difficulties to systematize the information (Table 2) and characterize each case study accordingly. Occasionally, it was necessary to proceed with a web search on local electricity companies′ annual reports and other sources to complement the information from scientific publications.

Table 2
Characterization of indicators.

Community characterization	Renewable hybrid system details
Geographical site	Percentage of renewable energy provided by the system
Population	Type of energy supply
Economic activity	Type of storage
Water resource	Methodology or software to optimize system design
Type of grid connection	Application
Electricity demand	

2.1. Community characterization

The location of the community (continent and country) is important to know as electricity demand patterns differ with geographical site and cultural habits. The population is an important indicator to understand how demand per capita differs from region to region, especially between the Northern hemisphere countries and South ones. The economic structure also affects the energy demand, thus we considered the existence of the economic activities of farming, fishing and agriculture (primary sector), industry (secondary sector) and tourism and services (tertiary sector).

In the particular case of islands, water resource can be scarce or inexistent, especially those in dry climates. Due to geographical isolation, the water may be imported (in general using boats increasing largely their energy bill) or use desalinization processes, which are large energy consumers, and therefore may have an important weight in electricity demand of small communities without industry sector.

Characterizing the systems as stand-alone or grid-connected systems is important to understand some implementation choices regarding renewable penetration and system operation. On stand-alone projects, normally we find technical studies and economic evaluations that are more accurate, as the systems have to be capable to respond to peak load by themselves, even when there is few renewable resources available, and there is the need for a reliable backup and storage systems. Knowing the type of grid connection, is possible to consider different scenarios and study the improvements of adding HRES to the grid.

Finally, having a detailed characterization of yearly electricity demand for each case study, allows us to understand the magnitude of the consumption needs in these communities as a reference to designing the systems that can respond to them. Having also the demand growth rate is important, as this type of systems has to be reliable (and so, well dimensioned) and cannot collapse with an increase of the demand due to the provision of more services to a certain community.

2.2. Hybrid renewable energy system details

To describe the type of HRES, we start by considering the percentage of renewable penetration on the total delivered energy. This provides us with an idea of what kind of system it is: mainly renewable with some kind of backup or based on a previous supply system with some additional support from renewables.

The description of the resources availability is important to find patterns of application and success of these hybrid systems, and to understand the preference of certain technologies over others.

The description of the storage system works as an indicator of the state of the market, and the (dis)trust that experts put on certain technologies. For example, the type of storage technologies used on stand-alone systems, which normally are exposed to exhausting life cycles, gives us an idea of the real level of reliability on renewable-storage coupled systems.

In some studies, we see the use of some optimization tools to obtain the system design, using a certain methodology or software. Its use allows the definition of the best possible option to achieve the HRES with predefined goals at minimum cost. With optimization tools becoming more popular, it is interesting to see its effectiveness through the comparison and/or validation before and after the project.

In this perspective, we categorize the case studies regarding its application. Only with real case studies and its results, we can step forward to validate the models, facing in situ problems and learn from them.

3. Comparative review

In this section, we present the comparative review of the case studies analyzed, based on the indicators previously presented for two types of locations: islands and remote villages.

3.1. Islands

The values represented in Table 3 were found on a large literature review, between scientific papers and government and electricity companies′ data. In some cases, national or regional values of demand per inhabitant had to be taken into account, to estimate the island demand.

3.1.1. Island characterization

Looking at Table 3a,b, we find that this type of projects take place all across the world, though most of the cases are in European islands. In terms of population, though we considered studies up to 100,000 inhabitants, most of the cases have been done to smaller populations ($<10{,}000$).

The main economic activities carried out in these islands belong in general to the primary sector, this is, farming, fishing and agriculture for self-sufficiency. In larger islands (>2000 people), we start to find more tourism activities than subsistence ones, which has an impact on energy consumption. Taking, as last example, the case of Gotland, Sweden, we also see that the existence of industry (concrete production) influences heavily the energy demand values.

Normally we could expect an increase of energy demand with population, but as we can see in Fig. 1, only in smaller communities (under 10,000) that is true. When we account with larger communities, this relation is not linear anymore. There we see, for example, that South Kiribati has a demand of only 8062.2 MWh/year for a population over 40,000 people, compared for instance with Gotland, Sweden, where the demand is 754.000 MWh/year for a population of 57,000 people. This discrepancy is related to the differences in existing economic activities, geographical site and eventually cultural aspects.

In the zoom of 10,000 people, in Fig. 1, we see that albeit some dispersion, we can assume a linear relationship between the demand and the population. The exceptions are

- The islands which present higher demand per capita are all located in developed countries (four in Europe and one in Australia) and they all have tourism activity; Porto Santo has also a water desalination power plant, which explains the higher consumption.
- The islands which present lower consumption are located in Asia and Oceania, in developing countries where the economic activities are still from the primary sector.

In Fig. 2, we can compare how electricity demand per capita changes by continent. The demand per capita per year on the European islands is on a range of 1000–14,000 kWh/capita/year, showing that Europe divides itself in different patterns of demand due to its geographical, cultural and economic heterogeneity. On the other hand, if we look to Asia we see a smaller range of 30–4000 kWh/capita/year, where typically we have very low demand on islands isolated by the ocean, and larger islands connected to the main country, where the access of goods is easier and with higher consumption. Also in Oceania, this demand is influenced by the fact that they are part of the Commonwealth of Australia (Norfolk Island, King Island, Chatman Island) or are an isolated island country (Fiji, Kiribati), leading to a discrepancy of 3000–7500 kWh/capita/year and 200–300 kWh/capita/year, respectively. In North America, we find

Table 3a
Island case studies comparative review – Island characterization.

Island characterization							
Continent	Name/Country	Population (number)	Economic Activity	Water Resource	Type of grid connection	Demand (MWh/ year)	Demand Growth Rate (%/year)
Europe	Community in Utsira, Norway	212	N/A	N/A	Connected	246	N/A
Europe	Corvo, Azores, Portugal	425	Farming, fishing	rainfall collection	Isolated	1400	7.20%
Europe	Ventotene, Italy	580	Tourism	Imported	Isolated	531	N/A
Oceania	Chatham Islands, New Zealand	600	Farming, fishing	N/A	Isolated	2370	N/A
Asia	Nolhivaranfaru, Maldives	650	Fishing & tourism	N/A	Isolated	111	12%
Europe	Mljet, Croatia	1111	Farming, fishing, agriculture & tourism	Desalinization + imported	Connected	4640	7%
Europe	Pellworm Island, Germany	1200	Farming & tourism	N/A	Connected	11250	N/A
North America	Fox Islands, Maine, USA	1550	Fishing	N/A	Connected	11793.6	N/A
Europe	Kithnos, Greece	1600	Tourism	N/A	Isolated	5630.2	N/A
Oceania	King Island, Tasmania	1723	Tourism, industry, fishing & farming	N/A	Isolated	12870	N/A
Oceania	Norfolk Island, Australia	2302	Tourism	N/A	Isolated	7900	N/A
Oceania	Rotuma Island, Fijis	2500	Farming, fishing	Rainfall collection	Isolated	876	N/A
Europe	Salina Island, Sicily, Italy	2504	Tourism	N/A	Isolated	10859.5	1.8%
Asia	Pangan-an, Philipines	2800	Fishing	N/A	Isolated	30.2	N/A
Asia	Neil Island, India	2806	Agriculture, farming	field water, rainfall collection	Isolated	843.15	N/A
Europe	Flores, Azores, Portugal	4099	Farming, fishing & services	N/A	Isolated	11370	3.80%
Europe	Samso, Denmark	4300	Agriculture, farming & tourism	N/A	Connected	27000	N/A
Europe	Graciosa, Azores, Portugal	4879	Farming, fishing & services, tourism	N/A	Isolated	13090	3.90%
Europe	Porto Santo, Portugal	5000	Tourism	Desalinization	Isolated	40000	1.90%
Asia	Peng Chau, Hong Kong	6000	Tourism	N/A	Connected	21750	2.0%
Europe	Karpathos, Greece	6511	Tourism	N/A	Isolated	25956.4	4.7%
Europe	Mykonos, Greece	10000	Tourism	N/A	Connected	43612	N/A
Europe	El Hierro, Canary Islands, Spain	10000	Tourism	Desalinization	Isolated	41530	N/A
North America	Bonaire Island, Netherlands	14500	Agriculture & tourism	N/A	Isolated	75000	N/A
Africa	Sal, Cape Verde	20000	Agriculture, fishing & tourism	Desalinization	Isolated	29092	4.90%
Oceania	South Tarawa, Kiribati (atols)	40311	Agriculture, fishing	ground water	Isolated	8062.2	28%
Europe	Gotland, Sweden	57000	Agriculture, Farming, Industry, Tourism	N/A	Connected	754000	N/A
Asia	Kinmen Island, Taiwan	84570	Tourism, services	N/A	Isolated	254452.3	4%

Table 3b
Island case studies comparative review – Energy system characterization.

Energy System Characterization								
Continent	Name/Country	Type of previous supply	RES %	Type of Supply	Type of Storage	Methodology / Software	Application	Study
Europe	Community in Utsira, Norway	Grid	50-65%	Wind (stand-alone system)	Hydrogen gas storage+fuel cells	TRNSYS+HYDROGEMS	Applied	[12]
Europe	Corvo, Azores, Portugal	Diesel power plant (DPP)	70%	Wind+PV+DPP	Flywheel	HOMER	Being applied	[13–15]
Europe	Ventotene, Italy	Diesel power plant+Photovoltaic	60%	Wind+PV+Wave+DPP+(ST+EE+DSM)	H2 Fuel Cells	TRNSYS	Evaluation only	[16,17]
Oceania	Chatham Islands, New Zealand	Diesel power plant	47%	Wind+DPP	N/A	N/A	Being applied	[18]
Asia	Nolhivaranfaru, Maldives	Diesel power plant	57%	Wind+DPP	N/A	HOMER	Evaluation only	[19]
Europe	Mljet, Croatia	Grid	50%	Wind+PV (stand-alone system)	H2 Fuel Cells	H2RES	Evaluation only	[20]
Europe	Pellworm Island, Germany	Grid	100%	Wind+PV+Biogas	N/A	N/A	Applied	[21,22]
North America	Fox Islands, Maine, USA	Grid	74%	Wind+Grid	N/A	N/A	Applied	[23,24]
Europe	Kithnos, Greece	Diesel power plant+ Wind+Photovoltaic	33%	Wind+PV+DPP	Batteries	Simulink	Applied	[25–27]
Oceania	King Island, Tasmania	Diesel power plant+Wind	65%	Wind+PV+Biodiesel+DPP	Batteries	N/A	Being applied	[28,29]
Oceania	Norfolk Island, Australia	Diesel power plant	60%	Wind+PV+DPP	H2 Fuel Cells	N/A	Evaluation only	[30]
Oceania	Rotuma Island, Fijis	Diesel power plant	N/A	PV+DPP	Batteries	HOMER+surveys	Evaluation only	[31]
Europe	Salina Island, Sicily, Italy	Diesel power plant	18-40%	Wind+PV+PDG (home systems)	N/A	TRNSYS	Evaluation only	[32]
Asia	Pangan-an, Philipines	Private diesel generators+Photovoltaic	80%	PV+PDG	Batteries	survey	Applied	[33]
Asia	Neil Island, India	Private Diesel generator	100%	PV+Biogas+Biomass gasification	Batteries	local data+survey	Evaluation only	[34]
Europe	Flores, Azores, Portugal	Diesel power plant	54%	Wind+Hydro+DPP	Flywheel	N/A	Applied	[35]
Europe	Samso, Denmark	Grid	100%	Wind+Grid	N/A	N/A	Applied	[36–38]
Europe	Graciosa, Azores, Portugal	Diesel power plant+Wind	70%	Wind+PV+DPP	Batteries	N/A	Being applied	[35,39]
Europe	Porto Santo, Portugal	Diesel power plant+Wind	45%	Wind+DPP	N/A	RenewIslands	Evaluation only	[40]
Asia	Peng Chau, Hong Kong	Grid	100%	Wind+PV+Grid	N/A	N/A	Evaluation only	[41]
Europe	Karpathos, Greece	Diesel power plant+Wind	20%	Wind+PV+DPP	N/A	HOMER	Being applied	[42]
Europe	Mykonos, Greece	Diesel power plant+Wind	18%	Wind+PV+DPP	N/A	N/A	Being applied	[43]
Europe	El Hierro, Canary Islands, Spain	Diesel power plant	75-80%	Wind+DPP	Pumped Hydro	N/A	Being applied	[22,44,45]
North America	Bonaire Island, Netherlands	Diesel power plant	40-45%	Wind+Biodiesel+DPP	Batteries	N/A	Applied	[46]
Africa	Sal, Cape Verde	Diesel Power Plant	9%	DPP+wind+solar	N/A	N/A	Applied	[47]
Oceania	South Tarawa, Kiribati (atols)	Petroleum+Biomass+Photovoltaic	25%	PV+Biomass+Petroleum	N/A	N/A	Applied	[48,49]
Europe	Gotland, Sweden	Grid	25%	Wind+PV+Biomass+Grid	N/A	N/A	Applied	[50]
Asia	Kinmen Island, Taiwan	Diesel power plant	34%	Wind+PV+DPP	N/A	N/A	Evaluation only	[51]

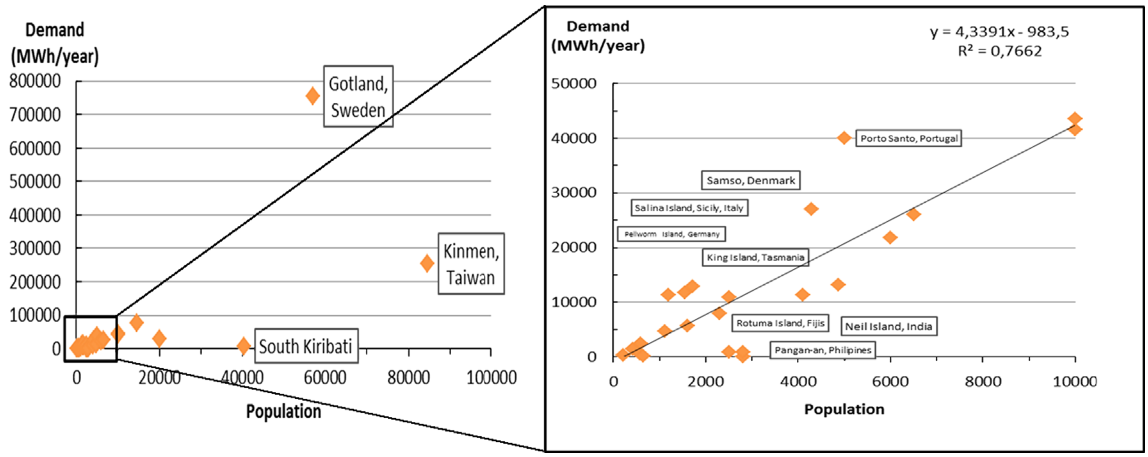

Fig. 1. Electricity demand versus population (whole range up to 100,000 population and zoomed in to 10,000).

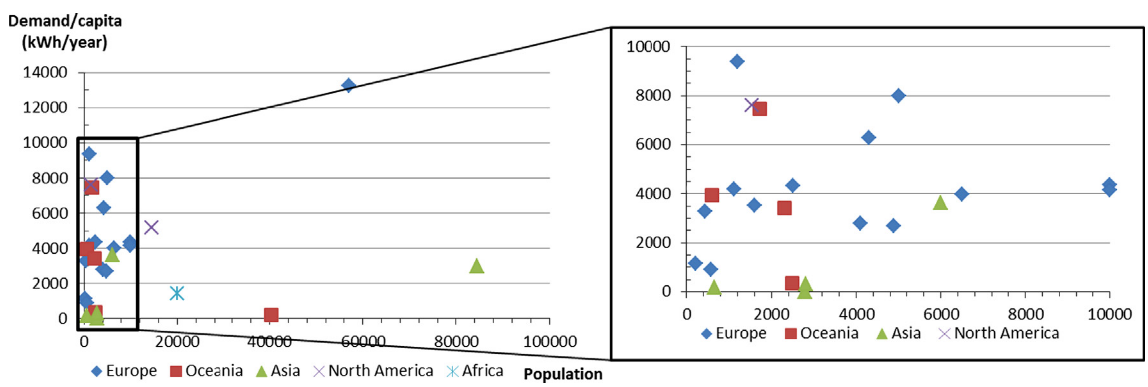

Fig. 2. Electricity demand per capita according to geographical site and population.

the difference from Caribbean Countries to Northern States, which imply a difference of 5000–8000 kWh/capita/year, being America the continent that has the highest beginning range. For Africa we used only one case study (Sal, Cape Verde), that presents a demand about 1500 kWh/capita, that due to tourism and the existence of a water desalination plant it is not so low as we could expect (as the rest of Africa), but still is very low compared to other continents.

3.1.2. HRES characterization

Regarding the type of existing supply systems, we see in Table 3 that diesel power plants (DPP) dominate the supply (39%), except for grid-connected cases (25%), where the energy mix depends largely on the mainland grid. However, we can observe already a significant number of hybrid systems of DPP/Wind (18%). Other combinations of hybrid systems, depending on the type of endogenous resources, are available in each case and consider mixes of different renewable sources like wind, solar photovoltaic (PV) and biomass. We can also see that in some remote islands with very low demand, we do not find a grid managed by the government. In these cases, local private generation units, denominated in this study Private Diesel Generator (PDG), assure the demand.

In Fig. 3, we can see the relation between type of system and demand per capita. This graph shows that private generators and photovoltaic systems are applied only in low demand cases, being the DPP and DPP/Wind systems, which are connected to grid, the ones used for larger demands. We also see that DPP is commonly used to respond to a large spectrum of cases, which show that it is still the most flexible technology to adjust to different types of demand.

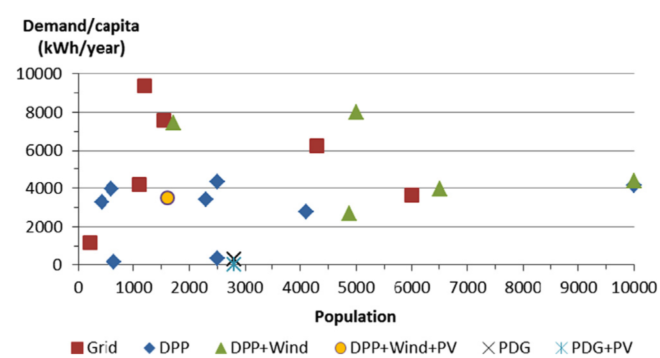

Fig. 3. Distribution of existing supply systems by demand per capita and population bellow 10,000 people.

In terms of state of application from the 28 cases studied, we find that the majority (39.3%) is already applied, 25% is still being applied, and only 35.7% were not implemented yet.

Many of the projects that are only at the evaluation level are academic paper studies/thesis, to test a certain hypothesis, but there are also many examples of papers that explore the feasibility of a real economic investment, its risks and possible barriers. At an implementation level (applied or being applied), there are more studies regarding HRES design choices and in some cases after-analysis of implemented projects.

Another important detail is the fact that some of these projects refer to technology demonstrations. These projects focus on the integration of a certain renewable technology or storage system on a controlled environment, which does not necessarily represent the dynamics of the entire system or micro-community (e.g.

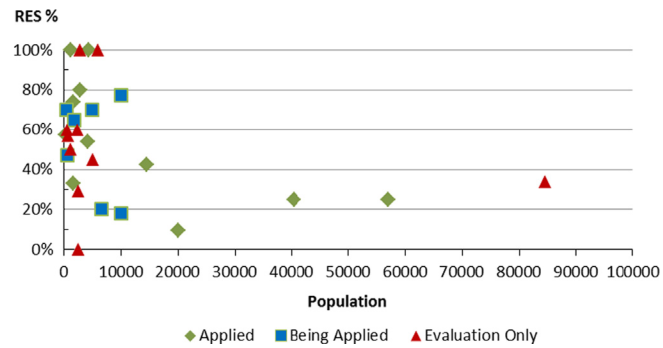

Fig. 4. Distribution of projects by its application, renewable penetration and population.

Utsira, Norway [12] or Unst, Scotland [2]). Thus, the percentage of RES and the success of the technology integration in the global system may be overestimated. The number of long-term global analyses of islands is much smaller, but more interesting on a sustainable perspective, and from where we can learn more about islands dynamics.

As we look more closely in Fig. 4, to the percentage of renewable energy penetration on the total delivered energy (% RES), we can see that the values span from 0% to 100%, but most of the cases are in the range between 20% and 80%. We can see also that we have two cases of real implementation that achieve 100%: Samso, Denmark and Pellworm in Germany. Both cases are in Europe, connected to the mainland and with a small population (less than 5000 inhabitants). In both, there are large renewable power plants (wind in Samso, and photovoltaic and wind in Pellworm) that produce more energy than the total energy demand. Overall, the net balance is positive (the island produces more electricity than it needs) but when we look to a higher temporal resolution, it may happen that in some periods of the day the islands are consuming some power from the mainland that is not 100% renewable. So is fairer to call them net zero islands or net positive energy islands, than self-sustainable islands. However, from the presented case studies, only 29% are grid connected.

In Table 4, we see the percentage of projects that used each resource (alone or combined). We can conclude that Photovoltaic is still a second option, after wind. The main reason for the choice for wind is due to its economic competitiveness with traditional fuel technologies. However, the evaluation of the cost-benefit analysis has to take into consideration the intermittence of the renewable resources. Thus, on a long-term perspective, it is necessary to account with daily and seasonal variability, and especially with its combination, regarding economic activities and structure of growth. Configurations with more than two renewable technologies tend to be residual - due to complexity of the system and more investment and operation costs.

In any case, the connection to other grid or diesel power plants have always to be available to assure the reliability of the grid, when the renewable resource is not available, but also to control the quality of the system. That is why in isolated systems, even if the resource is available, the diesel generation will always be partially on use and making it virtually impossible to go beyond 80%. The only way to avoid the use of diesel generation and achieving 100% is including storage in the system.

This fact proves the trend of studying and investing on renewable technologies for stand-alone systems like in islands, where the cost benefit analysis is usually positive for the renewables technologies. In any case, it is also interesting to notice that from all stand-alone cases (implemented or not) above 5000 people, HRES are not able to integrate more than 50% of renewable. Except for the case of El Hierro, with 10,000 inhabitants that expects to achieve 80% of penetration with the help of a hydro pump storage system. These HRES have necessarily to consider storage technologies, using normally batteries for low demands, that are not economically viable on a large scale. We also can conclude that this percentage of RES is more dependent on the electricity end-use than on the total population.

To tackle the difficulties around the implementation of storage systems (both technical and economic) we observe some sub-dimensioning of renewable systems in order to have reliable systems where diesel is the main energy source, leading in some cases to small RES penetration.

If we pay attention to the HRES configurations proposed for the different studies in Table 3, we see that the combinations can be innumerous. Wind energy is almost a common denominator in these systems, being the DPP/Wind/Photovoltaic and DPP/Wind the more popular, with 28% and 14% of the cases, respectively. These combinations are the ones most used in the projects currently being applied.

In Fig. 5, we present the percentage of cases that consider storage technology (50%) by type of technology. The projects that do not use storage technologies and are stand-alone systems, do not achieve more than 25% of renewable penetration. We can see that batteries continue to have a major role on this type of systems, especially on the real applied cases, as batteries are able to provide energy in case of resource unavailability, but also contribute to supply quality control. On the other hand, pumped hydro can only be used if the geographical conditions allow for it (existence of water and altitude). We also observed some experimental case studies [20,52] using fuel cells with hydrogen, that are still not economically viable on a large scale. All the technologies are at least applied once (one case study with flywheel, three with batteries and one H_2 fuel cell).

Taking a more deep thought on the real role of electricity storage, we find that it can be quite diverse regarding the type of storage we want to achieve. For islands, we think that we need more complete storage systems, capable of storing renewable electricity from multiple hours to multiple days (like pumped hydro in El Hierro, Canary Islands, Spain, being applied). At the same time, power quality technologies (like flywheels) are still important to face the impact that renewables' intermittency causes on the grid. Systems with no storage availability (N/A) are

Table 4
Number of projects that used each resource.

Diesel (%)	Wind (%)	Photovoltaic (%)	Biodiesel/biogas/ biomass (%)	Hydro (%)	Wave (%)	Grid (%)
68	86	64	21	4	4	11

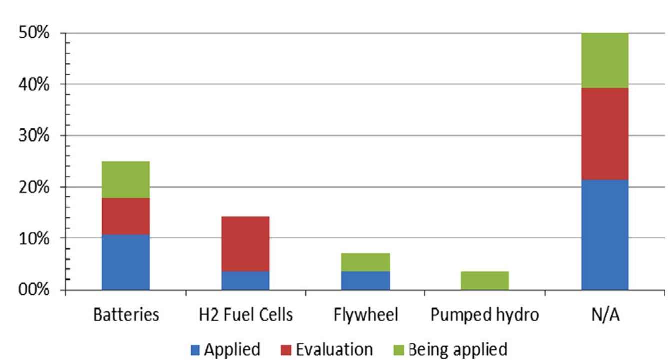

Fig. 5. Storage technologies studied.

the systems that are connect to the grid or do not present any information about it.

Regarding methodology of optimization of the projects, we see that only 39% of the case studies used some type of methodology or software. The use of methodologies has larger incidence on academic and experimental studies (70%) but few are used on real applied projects (18.2%). On case studies that are still being applied or already applied, we see in general that most use HOMER [53]. In projects that consider only evaluation, we observe a more diverse use of methodologies like *RenewIslands* [54], H2RES [20], TRNSYS [55], *Simulink* [56] or local surveys.

3.2. Remote villages

Another important set of isolated micro-communities is the case of remote villages. In general, they differ from the islands in the sense that, albeit they are isolated in terms of energy access, these communities are not completely geographically isolated and this has an impact in some of the variables that were analyzed for islands, such as the possibility of grid-connection.

In remote villages, it is very difficult to characterize demand due to the lack of systematic information about the community. Most communities are not connected to electric grid and when they are, the connection quality and service is very low. At the household level, they use biomass and/or kerosene for cooking, lighting and heating, which makes it difficult to quantify and then generalize energy demand values for the community. From these values, it is possible to make some kind of assumptions regarding electricity demand to design a system. Thus, in fact, we are characterizing electric demand by household (kWh/household) instead of community energy demand, being the community demand the cumulative consumption of the households (hh). This restricts openly the study to residential demand, once this type of isolated communities, normally, don't have any other energy consumption sector. This is a fairer indicator than demand per capita is, as we are able to compare directly specific energy needs. Table 5 presents the overview, following the same type of indicators.

3.2.1. Remote village characterization

Looking to community energy demand on Table 5, we see that it ranges from 1 to 55 MWh/year, except for the case of Lucingweni, in South Africa that present a value of 245.3 MWh/year. As we do not know the number of people living in each household, we can assume that there are significant differences in social and economic conditions that explain this discrepancy. For example, in a village with few hundred households, it is probable that some economic activity exists related to the support of village itself (e.g. small shops, schools, community centers). In general, we can observe that villages have less than 60 households and less than 50 MWh/year of demand.

When we consider energy demand per household, as showed in Fig. 6, we see some changes. For South America, the values are very low (115 kWh/hh/year), while for Asia, we can find values between 365 and 705 kWh/hh/year, except in the case of Iran, with an extremely high value of 5278 kWh/hh/year (which can be explained by the heating demand in the cold climate with the proximity of mountains). In the case of Africa, values oscillate in a range of 79–2200 kWh/hh/year. In conclusion, we are talking about a limit of 2200 kWh/hh/year for villages above 100 households and a limit of 1200 kWh/hh/year for villages under 100 households.

3.2.2. HRES characterization

Regarding the type of supply, we see that, except for one case study in Africa, all the cases are supplied by diesel. We also

Table 5
Remote villages case studies comparative review.

Remote village characterization								Energy system characterization						
Continent	Name/Country	Population (households)	Economic activity	Grid	Demand (kWh/hh/year)	Demand (MWh/year)	Demand growth rate (%/year)	Type of previous supply	% RES	Type of supply	Storage	Methodology/ Software	Application	Study
Asia	Sheikh Abolhassan, Iran	10	Subsistence	Connected (since 2006)	5278	52.78	N/A	Grid	45	Wind+PV+PDG (isolated)	Batteries	HOMER	Evaluation only	[57]
Africa	North Garoua, Cameroon	19	Subsistence	Isolated	79–365	1.3–6.9	N/A	N/A	60	PV+LPG	Batteries	HOMER	Evaluation only	[58]
Africa	Adar, Algeria	20	Subsistence	Isolated	1168	23.36	N/A	Diesel generators	100	Wind+PV+PDG	Batteries	HOMER	Evaluation only	[59]
South America	La Ciénaga, Argentina	23	Subsistence	None	115	N/A	N/A	N/A	100	PV (home systems)	Batteries	N/A	Applied	[60]
Asia	Dinajpur district, Bangladesh	50	Subsistence	Isolated	365	18.25	N/A	N/A	43	PV+PDG	Batteries	HOMER	Evaluation only	[61]
Asia	Long Beruang, Malaysia	54	Stone collecting	Isolated	705.5	38.1	N/A	Private diesel generators (PDG)	100	PV+PDG	Batteries	N/A	Applied	[62]
Africa	Lucingweni, South Africa	112	Subsistence	Isolated	2190	245.3	6.00	N/A	100	Wind+PV	Batteries	N/A	Applied	[63]

We studied more cases than the ones presented above, but they were not consider for several reasons. Like the case of the province of Jujuy in Argentine [64], a very remote region, are the houses where so dispersed that it did not make sense to consider them as part of the same community. Another case, is a successful implementation in Palestine [65] but we could not find enough system' quantitative data to compare with the other case studies. For the remote village of Rawdat Ben Habbas, on Saudi Arabia [66], we would only find energy demand in kWh/day/person, which did not allow us to compare with the other case-studies, where we don't find information about population but only for households. In conclusion, there is no systematized way to report the case studies, and it is very difficult sometimes to generalize and compare different indicators.

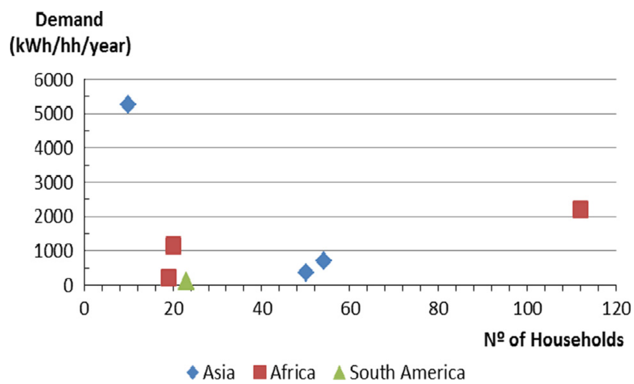

Fig. 6. Yearly energy demand per household by geographical site.

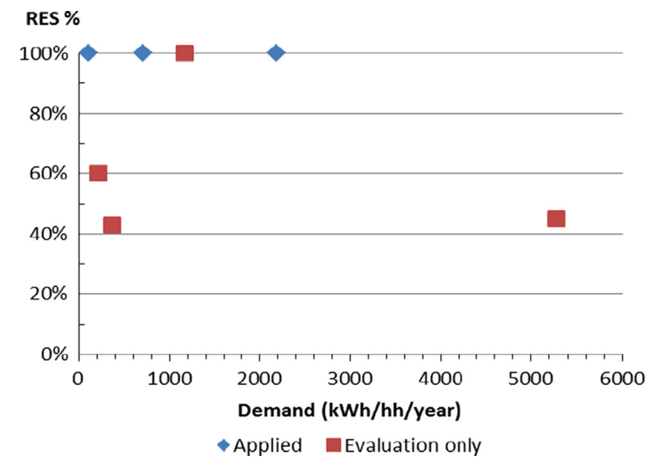

Fig. 7. Percentage of renewable source on the hybrid renewable systems.

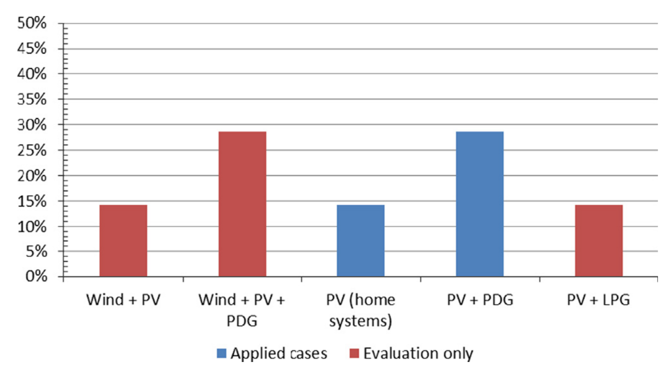

Fig. 8. Percentage of use of each type of hybrid system, on the analyzed case studies.

accounted that most of the remote villages studied are off-grid (86%), featuring only private devices. From all the cases analyzed, only one was (recently) grid connected.

Looking to the HRES solution for each case study, we see that 43% of projects were applied, which is consistent once again with the fact that in remote off-grid systems, the use of renewables can be cost-efficient.

On Fig. 7, we see 100% of the applied projects (3 out of 7 studied) have 100% renewable penetration. In these cases, apparently it is easier to meet the demand with pure renewable systems due to

- Low demand and lack of a previous organized infrastructure of supply.
- Normally, these systems are only requested for few hours per day (usually evening hours for lighting).

In these cases, the satisfaction on having electricity provided is very high.

On Fig. 8, we see that the most popular system on the applied cases is the Photovoltaic/PDG configuration, with almost 30% preference, followed by the combination of photovoltaic systems with battery backup. On the evaluation cases, we see also that wind/photovoltaic/PDG accounts for 30% of the cases and is proposed as a potential alternative to photovoltaic-only systems. In these cases, the diesel works in general as second backup supplier in extreme cases, as they are not part of the community electric system. Every other system considers batteries as storage technology, which, for small demands, is enough.

Regarding the use of methodology to optimize the system design, we found that 50% of the projects used HOMER [53] as design software. Interestingly, it was used only on projects that were evaluation cases – this demonstrates the adequacy and applicability of this software to this scale and type of communities, with increasing use in recent years. Thus, we can concluded that the current practice does not follow yet any methodological approach based on energy systems modeling and optimization.

3.3. Islands versus remote villages

Having presented an analysis for these two types of micro-communities, we can find some differences that are highlighted on Table 6.

The maximum demand on remote village (245.3 MWh/year) is near minimum demand on the island's case (111 MWh/year), and the maximum differs in two orders of magnitude. The main differences are on dimension and main activities, since normally on islands there is some use of natural resources (sea, fields, etc.) that will influence the electric demand. In islands, we must account also with tourism, which implies that system's design meet seasonal oscillations. This brings us a level of commitment between a reliable backup able to respond to peak demand (that normally is diesel), and a good percentage of renewable source able to ensure normal demand over the year. In Islands, differences between geographical site are more representative, and are related to the community activities and regional socio-economic development. In remote locations, we note higher percentages of renewable penetration due to the small size of the systems that must rely on batteries for backup and storage, and also to smaller range of working hours (evening).

In terms of grid-connection, there is a dominant difference, which is the possibility of remote villages to become grid connected (like happened with the case study of Sheikh Abolhassan, Iran). Normally that possibility is not viable on isolated islands, leading to an extra need for an accurate dimensioning of the hybrid systems, taking in account projections on growth rates, since these type of systems normally represent big investments for decades.

We note that the preferable HRES configurations are different. In islands, we have innumerous possible configurations due to dimension and heterogeneity of islands and renewable resource, but the abundance of wind resource on sea locations makes the majority Wind/Photovoltaic/DPP. In remote villages, systems oscillate between photovoltaic and diesel technologies since normally there is good solar resource and few reliable information of other resources, although some systems are starting to be complemented by micro wind turbines.

Renewable percentages of the hybrid renewable system demonstrate to be higher in remote villages (100% from photovoltaic combined with batteries) once electricity demand is very low and normally there was no electricity supplier before, leading to an initial period with no increasing demand and high satisfaction with the

Table 6
Comparison of main between islands and remote villages.

	Islands	Remote villages
Main activities	Fishing, farming, agriculture, tourism	*Subsistence*
Demand dimension	Differs greatly with geographical site [111–754,000] MWh/yearHigher peak demand – 24 h needs	[1.3–245.3] MWh/yearMostly requested only on evening hours
Grid connections	71% isolated – very costly or impossible to become connected to mainland grid	86% isolated – possibility of becoming connected to the grid
Major hybrid system configuration	Wind/Photovoltaic/Diesel power plant	Photovoltaic/Private diesel generator/Batteries
Major backup system	Diesel power plant (existing supplier and sub dimensioning of renewable systems) – more reliable	Batteries
Renewable penetration	Up to 80% for yearly demands lower than 20,000 MWh	Up to 100% for yearly demands lower than 2000 kWh/household
Economic overview	Public/cooperation investment (South) versus Private investment (North) Costly isolated backup technologies combined with renewable intermittency. Sustainable in long term analysis	
Social overview	More system success with population integration in the process of decision and caring [65] Night lighting in remote villages improve educational and social level [64,67,68]	

system. For these cases, we could not find demand growth values, but the experience from the installation of these projects says that after a while and in order to improve their welfare, communities tend to buy more appliances for which the system was not dimension [69]. This fact takes to additional wear of the batteries, shorting the life cycle of theses HRES.

In islands, we see a large range of renewable percentage on the applied cases: from 9% to 80% on stand-alone systems, and 25% to 100% on grid-connected systems. On the first cases, we notice that it is difficult to rely only on renewable source and storage systems. In bigger system's dimension, only pumped hydro is reliable enough to give security of supply, and achieve high percentages of renewable (see the case of El Hierro, on Canary Islands, that currently is being applied). However, pump hydro isn't a viable technology everywhere, per example, if access to potable water is a problem or if there is not a geographical slope. For that stand-alone cases we see that previous conventional energy supply systems, are predominant on the design of the new hybrid system, working as complementary backup and peak demand response, with the renewable technologies assuring a part of the demand over the year (but also with small percentages). Regarding grid-connected systems, we see that they achieve more easily 100% RES, since the local renewable production is higher than the local demand and they are connected on a larger national grid capable of absorbing and manage all these suppliers (see the case of Samso or Pellworm).

In terms of financial investment, we encounter some differences by region. In Northern islands, where normally green electricity and renewables are a culture and a pride, there is a tendency to have private investment (by users, municipalities or even some enterprises) on these hybrid systems, rather than a governmental/state investment. Grid connectivity can be a reason, making these projects less complex and costly than the ones standing alone. This contrasts with what happens in the Southern islands where HRES are normally financed by the national state or governments' cooperation's.

In some cases, the integration of renewables was reported together with the increased cost of energy, mostly for backup technologies (excluding diesel generators). This difference is only highlighted since the energy cost of conventional energy many times does not internalize transportation's cost (in remote communities this is usually high) or environmental costs (e.g. associate CO_2 emissions taxes). This is also the reason why there are some international programs of cooperation, which assure that all parts of the agreement are doing an effort for the world environment and climate change.

On a social level, from what we could access, HRES are more successful when integrate the population in the process of discussion, decision and implementation than when it is an "outside" decision without choice. In remote villages in particular, we also find a major contribute of night lighting to improve people lifestyle and wealth development, allowing to do school's homework (improving education) and to use sociability spaces between the community, especially to women, outside their personal space. The social opportunity that HRES bring, can help meeting some of the millennium goals for development [70], like helping to achieve universal primary education, promote gender equality and empowerment of women, ensure environment sustainability or even help to develop global partnerships.

3.4. Reporting framework for HRES projects

Based on the analysis of the different hybrid renewable energy systems and considering the difficulties to systematize information from the different projects, we suggest the works on the design, analysis and implementation of this type of system use the following framework to report the data:

- **Regarding electric/energy demand**: hourly, weekly, monthly and yearly demand profiles; off-peak and peak load (to account season oscillations); description of the energy use activities by economic activities and general economic growth rate; population size, population growth rate, number of households; any special feature that may influence significantly the energy demand (such as the existence of a special facility like a manufacturing plant or a hotel resort).
- **Regarding the energy system technical details**: design of the current supply system, including power of the generation plants; renewable resources availability and variability (daily, monthly); technical details about the generation and storage solutions (manufacturer, efficiency, power, etc.).

These factors are determinant to the design of a HRES, not only in terms of reliability and robustness, as well as in terms of percentage of renewable penetration, but also in terms of match between demand and supply. In this way, the comparison and benchmarking among the different projects can only be achieved if the reported data accounts for all these variables.

4. Conclusions

With this review, we can conclude that the interest for hybrid renewable energy systems is increasing in the world, as a way to provide sustainable energy independence for small communities.

The more common configuration of hybrid systems in islands is wind/photovoltaic/DPP (among many other possible configurations) and in remote villages, photovoltaic/PDG coupled with batteries (few possible configurations).

Storage technologies continue to be a challenge for islands in terms of efficiency and economics. In most cases are not viable with the present *state of the art*, especially for large scale hybrid systems with different energy suppliers, were the most appropriate option is pumped hydro that depends on the existing geographical conditions. Until storage technology evolves for large systems, it will be difficult to go over 50% of renewable penetration on HRES. In remote villages, batteries are currently a good technical and economical choice.

We denote also an increase on the use of methodologies to design the energy systems of isolated micro-communities. The methodologies are still more applied on the case of remote villages, where they demonstrated more accuracy (system's scale is smaller than in islands). These methodologies have been generalized to island case studies in the more recent years, especially for islands smaller than 10,000 people. In bigger islands, with different main economic activities starts to be difficult to manage all the demand patterns.

Definitely, improvements for HRES in isolated islands go for

- More accurate study of demand estimation, and multiple renewable resource dynamics and variability on the hybrid system's design, aiming to security of supply;
- more reliable storage systems, decreasing progressively the use of conventional energy suppliers (like fuel) and taking in account the type of storage role we need (multiple day or daily storage, power quality, etc.) adapting the type of technology and design of the system;
- use methodology tools to optimize the systems, encompassing four main vectors: island economic structure (and so demand), renewable resource estimation, adequacy of storage technologies, and real investments projection;
- considering public economic investment in these systems as a necessary effort as developer of economic and educational level and welfare, approaching these communities from self-sustainability;
- and, of course, the success of these systems would have to bring the population closer to the project's decision and implementation.

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